Model of the tail region of the heliospheric interface

Vlad Izmodenov[*]
Lomonosov Moscow State University, Moscow, Russia

Dmitry Alexashov[†]
Institute for Problems in Mechanics Russian Academy of Sciences

Physical processes in the tail of the solar wind interaction region with the partially ionized local interstellar medium are investigated in a framework of the self-consistent kinetic-gas dynamic model. It is shown that the charge exchange process of the hydrogen atoms with the plasma protons results in suppression of the gas dynamic instabilities and disappearance the contact discontinuity at sufficiently (3000 AU) large distances from the Sun. The solar wind plasma temperature decreases and, ultimately, the parameters of the plasma and hydrogen atoms approach to the corresponding parameters of the unperturbed interstellar medium at large heliocentric distances.

I. INTRODUCTION

The Sun and its solar system are presently moving in the partly ionized local interstellar cloud (LIC) (e.g., Lallement, 1996). Direct measurements of interstellar atoms of helium (Witte et al., 1996) by GAS/Ulysses experiment show that the velocity of relative Sun-LIC motion is about 25 km/sec, and local interstellar temperature is about 6000 K. Other interstellar parameters, such as interstellar ionization state, densities of neutral and charged components, magnitude and direction of the interstellar magnetic field, can be determined by remote space experiments. These are e measurements of backscattered solar Lyman α radiation on boards of SOHO, Voyager, Pioneer spacecraft, pickup ions on boards of Ulysses and ACE spacecraft, the solar wind properties at large heliocentric distances by Voyager, absorption of Lyman α spectra toward nearby stars, and heliospheric fluxes of energetic neutral atoms (ENA). An adequate theoretical model of the solar wind interaction with LIC is needed to interpret the remote experiments. Theoretical concept of the solar wind interaction with the solar wind was proposed in the pioneer paper by Baranov et al. (1970). During last 30 years the model was significantly advanced by several research groups (for review see, e.g., Izmodenov 2000, 2002).

The structure of the Solar Wind - LIC interaction region is shown in Figure 1. Contact discontinuity, or *the heliopause* (HP), separates the solar wind and interstellar plasmas. The heliopause is an obstacle for both the supersonic (the Mach number is about 10) solar wind, and the supersonic (the Mach number is about 2) interstellar gas. A shock has to be formed in the case of supersonic flow around an obstacle. The supersonic solar wind passes through *the termination shock* (TS) to become subsonic. *The bow shock* decelerates the local interstellar gas from supersonic to subsonic. The whole region of the solar wind interaction is called *the heliospheric interface.*

Note, however, that in the case when effect of interstellar atoms is not taken into account, the qualitative picture of the tail flow pattern is more complex. The solar wind flow is subsonic in the nose part of the region between the termination shock and the heliopause. Then the flow passes through the sonic line (Baranov and Malama, 1993) and becomes supersonic. This results in formation of the Mach disk (MD), tangential discontinuity (TD) and reflected shock (RS) in the tail region (figure 1a).

The interstellar H atoms interact with plasma component by charge exchange and strongly influence locations of the shocks and the heliopause and the structure of the heliospheric interface. The main difficulty to model the heliospheric interface is a large mean free path of the H atoms with respect to charge exchange. The mean free path is comparable with the characteristic size of the heliosphere. Therefore, to describe interstellar H atom flow in the heliospheric interface it is necessary to solve kinetic equation. A self-consistent two-component (plasma and H atoms) model of the heliospheric interface was proposed by Baranov et al. (1991) and realized by Baranov and Malama (1993). The latter paper also presented the first numerical simulations of the heliotail. Figure 1 compares the geometrical pattern - locations of the two shocks and the heliopause - for the model, which takes into account the influence of interstellar H atoms, with the model, which do not take into account the neutral component. It is seen that the discontinuities are significantly closer to the Sun in the case with atoms. In the heliotail region the structure of the plasma flow changes qualitatively. The termination shock becomes more spherical and Mach Disk (MD), reflected shock (RS) and tangential discontinuity (TD) disappear (Figure 1).

The model of the heliospheric interface allows answering two fundamental questions: 1. Where is the edge of the solar system? 2. How far is the influence of the solar system on the surrounding interstellar medium?

To give an answer on the first question we need to

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[*]izmod@ipmnet.ru; `http://izmod.ipmnet.ru/~izmod/`
[†]alexash@ipmnet.ru

define the solar system boundary. It is naturally to assume the boundary is the heliopause, which separates the solar wind and interstellar plasmas. Note, that the influence of the solar system on the interstellar medium is significantly far than the heliopause. Secondary interstellar atoms, which are a result of charge exchange of the original interstellar H atoms and solar wind protons, disturb the interstellar gas upwind the bow shock. Detail studies of mutual influences of charge and neutral components in the heliospheric interface were done in Baranov and Malama (1993,1995, 1996), Baranov et al. (1998), Izmodenov et al. (1999, 2000, 2001). However, these papers were mainly focused on the upwind region. At the same time the study of the heliotail region has also significant interest. In the heliotail we cannot assume the heliopause to be the heliospheric boundary. It is seen in Figure 1, the heliopause is not closed surface and the solar wind fills the whole space into the downwind direction.

The goal of this work is to study the structure of the tail region of the heliospheric interface. We focus on the effects of the charge exchange process on the tail region.

II. MODEL

To study the effect of charge exchange on the structure of the heliotail we used kinetic-gas dynamic model by Baranov and Malama (1993). In this model the solar wind at the Earth's orbit is assumed to be spherical symmetrical and not varying with time. The interstellar flow is also assumed to be constant parallel flow. Under these conditions the flow in the interaction region is axisymmetric.

To describe the charged component (electrons and protons) we solve hydrodynamic Euler equations, where the effect of charge exchange is taken into account in the right parts of these equations. To calculate the flow of interstellar H atoms in the heliospheric interface we solve kinetic equation:

$$\mathbf{w}_\text{H} \cdot \frac{\partial f_\text{H}(\mathbf{r}, \mathbf{w}_\text{H})}{\partial \mathbf{r}} + \frac{\mathbf{F}}{m_\text{H}} \cdot \frac{\partial f_\text{H}(\mathbf{r}, \mathbf{w}_\text{H})}{\partial \mathbf{w}_\text{H}} \quad (1)$$

$$= -f_\text{H}(\mathbf{r}, \mathbf{w}_\text{H}) \int |\mathbf{w}_\text{H} - \mathbf{w}_p| \sigma_{ex}^{\text{HP}} f_p(\mathbf{r}, \mathbf{w}_p) d\mathbf{w}_p$$

$$+ f_p(\mathbf{r}, \mathbf{w}_\text{H}) \int |\mathbf{w}_\text{H}^* - \mathbf{w}_\text{H}| \sigma_{ex}^{\text{HP}} f_\text{H}(\mathbf{r}, \mathbf{w}_\text{H}^*) d\mathbf{w}_\text{H}^*$$

$$- (\beta_i + \beta_{\text{impact}}) f_\text{H}(\mathbf{r}, \mathbf{w}_\text{H}).$$

Here $f_\text{H}(\mathbf{r}, \mathbf{w}_\text{H})$ is velocity distribution function of H atoms; $f_p(\mathbf{r}, \mathbf{w}_p)$ is locally Maxwellian velocity distribution of protons; $\mathbf{w}_p$ and $\mathbf{w}_\text{H}$ is individual velocities of protons and H atoms, respectively; σ_{ex}^{HP} is the cross section of the charge exchange of H atoms and protons; β_i is the photoionization rate; m_H is the mass of H atom; β_{impact} is the electron impact ionization; and $\mathbf{F}$ is the sum of the solar gravitation and radiation pressure forces.

The main process of the plasma-neutral coupling is the charge exchange process $H + H^+ \rightarrow H^+ + H$. Photoionization and electron impact ionization are also taken into account in equation (1). The interaction of charged and neutral components results in exchange of mass, momentum and energy between these components. The source term $Q = (q_1, q2, z, q_{2,r}, q_3)^T$ is in the right part Euler equation for charged component. Here q_1, $\vec{q}_2 = (q_{2,z}, q_{2,r})^T$, q_3 are sources of mass, momentum and energy, respectively. The source terms are integrals of H atom velocity distribution function f_H:

$$q_1 = n_\text{H} \cdot (\beta_i + \beta_{impact}), n_\text{H} = \int f_\text{H}(\mathbf{w}_\text{H}) d\mathbf{w}_\text{H},$$

$$\vec{q}_2 = \int (\beta_i + \beta_{impact}) \mathbf{w}_\text{H} f_\text{H}(\mathbf{w}_\text{H}) d\mathbf{w}_\text{H} + \quad (2)$$

$$\int \int u \sigma_{ex}^{HP}(u)(\mathbf{w}_\text{H} - \mathbf{w}_p) f_\text{H}(\mathbf{w}_\text{H}) f_p(\mathbf{w}_p) d\mathbf{w}_\text{H} d\mathbf{w}_p,$$

$$q_3 = \int (\beta_i + \beta_{impact}) \frac{\mathbf{w}_\text{H}^2}{2} f_\text{H}(\mathbf{w}_\text{H}) d\mathbf{w}_\text{H} + \quad (3)$$

$$\frac{1}{2} \int \int u \sigma_{ex}(u)(\mathbf{w}_\text{H}^2 - \mathbf{w}_p^2) f_\text{H}(\mathbf{w}_\text{H}) f_p(\mathbf{w}_p) d\mathbf{w}_\text{H} d\mathbf{w}_p.$$

Here $u = |\mathbf{w}_\text{H} - \mathbf{w}_p|$ is relative atom-proton velocity.

For boundary conditions in the unperturbed LIC we adapt the velocity $V_{LIC} = 25$ km/s, interstellar H atom and proton number densities are $0.2\,\text{cm}^{-3}$ and $0.07\,\text{cm}^{-3}$. The temperature of the LIC was assumed 6000 K. Velocity, number density and Mach number at the Earth orbit are 450 km/s, $7\,\text{cm}^{-3}$ and 10, respectively. Velocity distribution function of H atoms is assumed to be Maxwellian.

Euler equations with the source term $\vec{Q}$ were solved self-consistently with the kinetic equation for H atoms. To get the self-consistent solution we used the iterative method. The kinetic equation was solved by Monte-Carlo method with splitting of trajectories. Unlike the previously published papers based on Baranov-Malama model, we performed the calculations in extended computation region toward the heliotail. We performed computations up to 50000 AU along the axis of symmetry and up to 5000 AU in the direction perpendicular to the axis of symmetry. To estimate divergence of chosen numerical scheme we used different computational grids. Dependence of the numerical solution from outer boundary conditions was estimated by variation of the computational domain in the tail region.

III. QUALITATIVE ANALYSIS

In this work we consider the effect of the charge exchange processes ($H + H^+ \rightarrow H^+ + H$) on the plasma flow in the tail region of the heliospheric interface. The
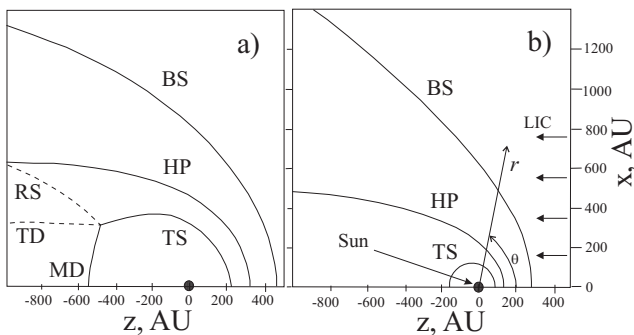
Figure 1: The structure of the heliospheric interface is the region of the solar wind interaction with the interstellar medium. HP is the heliopause, TS is the heliospheric termination shock, BS is the bow shock, MD is the Mach disk, TD is the tangential discontinuity, RS is the reflected shock. The right figure corresponds to the case with no H atoms, while the left figure corresponds to the solution, when interstellar H atoms are taken into account.

supersonic solar wind passes through the heliospheric termination shock, where its kinetic energy transfers into the thermal energy. Let us assume now that in the tail region the surface of the heliopause is parallel to the direction of the interstellar flow. This is in accordance with our numerical simulations. Under this assumption the solar wind can be considered as a flow in a nozzle having constant cross-section. Our computations show that in the case with no H atoms the solar wind pressure downstream the termination shock is several times smaller than the interstellar pressure. Under these conditions the solar wind flow decelerates and has some minimal value at infinity. The minimal value is determined by the parameters of the solar wind downstream the termination shock and the interstellar pressure. Neither the interstellar proton number density nor the relative Sun-LISM velocity does not determine the minimal velocity. Therefore, in the case with no atoms in the frame of hydrodynamic approach it is possible to find solution where the solar wind (and, therefore, the solar system) extended in the heliotail up to infinity. Such a qualitative consideration can be easily generalized, when the heliopause is not parallel to the axis of symmetry. Then the solar wind flow can be considered as a flow in convergent or expanding nozzle.

Qualitatively other situation is realized in the case when interstellar H atoms are taken into account. Our calculations show that in this case the solar wind pressure downwind the termination shock is larger than the interstellar pressure. The solar wind should be accelerated in this case by the pressure gradient. However, interstellar atoms play significant role due to charge exchange. The interstellar atoms fulfill the heliotail due to their large mean free path. Among the heliospheric H atoms the part of original (or primary) interstellar atoms increases significantly with the heliocentric distance. The temper-
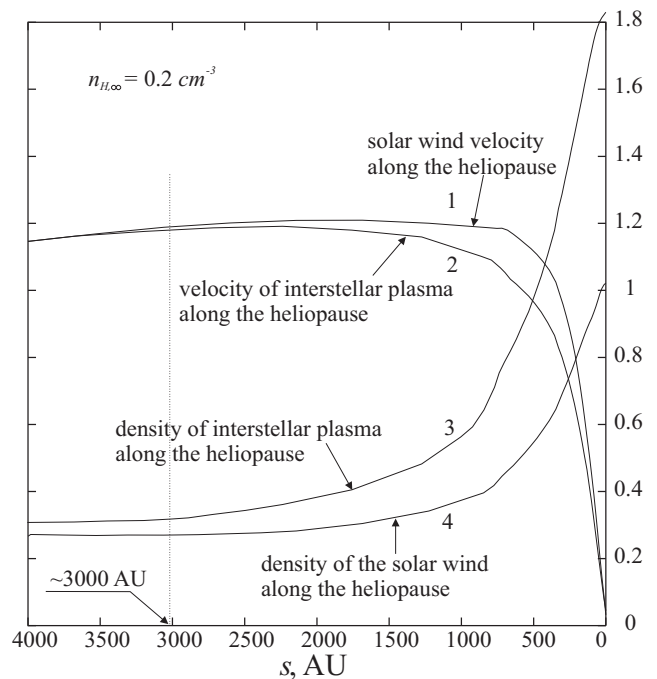

Figure 2: Velocities (curves 1 and 2) and densities (curves 3 and 4) from both sides of the heliopause as a function of the heliocentric distance along the heliopause. Curves 2 and 3 correspond to interstellar side; curves 1 and 4 correspond to solar wind side. The velocities and densities are normalized to their interstellar values.

ature (6000 K) and velocity (25 km/s) of the primary interstellar atoms are smaller than the velocity (100 km/s) and temperature (100000 K) of the post shocked solar wind. New protons, which are born from the interstellar H atoms, have smaller average and thermal velocities than original solar protons. Therefore, the charge exchange process leads to effective cooling and deceleration of the solar wind. The acceleration of the solar wind by the pressure gradient with one side and the deceleration of the solar wind by the charge exchange process may result in the heliopause is not always parallel to the axis of symmetry. Since the part of primary interstellar atoms increases with the increasing of the heliocentric distance, it is naturally to expect approach of the solar wind velocity, density and temperature to their interstellar values.

Despite a number of assumptions, qualitative analysis given in this section is confirmed by our numerical calculations. In the next section we present and discuss results of numerical calculations.

IV.   RESULTS AND DISCUSSION

Results of our calculation confirm the qualitative analysis given above. Distributions of plasma parameters in the heliotail region are presented in figures 2 and 3. Figure 2 presents the distributions of density and velocity of
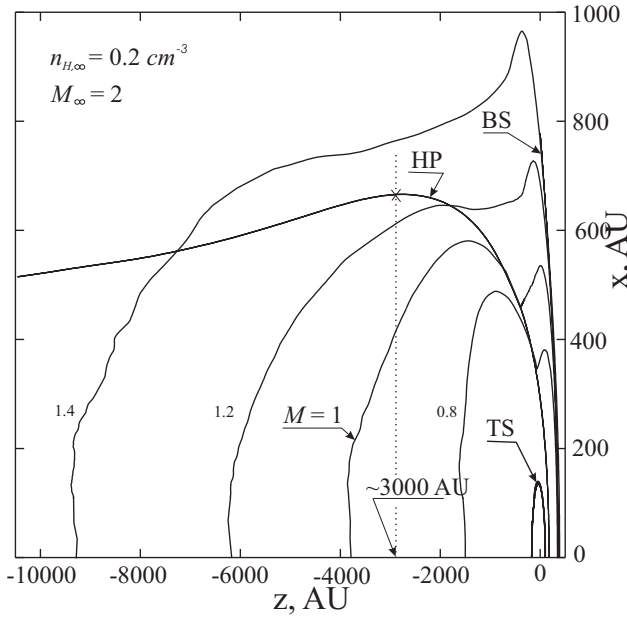
Figure 3: Isolines of Mach number M. It is seen that on the distances more than 4000 AU into the heliotail direction the solar wind flow is supersonic. The Mach number increases with increase of the heliocentric distance and approaches its interstellar number.

plasma along the heliopause. The parameters are shown from both interstellar and solar wind sides of the heliopause. In the classical hydrodynamics two conditions determine the tangential discontinuity. The conditions are 1) no mass transport through the discontinuity, 2) balance of pressures on the both sides of the discontinuity. These conditions permit a jump of density and tangential velocity through the heliopause. In the case with presence of interstellar H atoms the jump of density and pressure becomes weaker with increase of the distance calculated along the heliopause from its nose. This is due to mass transport caused by charge exchange. For $z \approx -3000$ AU, where z is the distance along the axis of symmetry and sign "-" means the direction toward the heliotail, the jump of density and tangential velocity disappears (Figure 2).

The velocity of the solar wind is about 100 km/s downstream the termination shock. Then the velocity becomes smaller due to new injected by charge exchange protons and approaches the value of interstellar velocity. The solar wind becomes also cooler due to charge exchange. The interstellar Mach number is ~2. It is interesting to see whether the solar wind becomes supersonic due to effective cooling. Figure 3 shows isolines of Mach numbers in the heliospheric interface. The solar wind passes through the sound velocity at about $z \approx$-4000 AU, then the Mach number increases approaching its interstellar value. The heliopause is also shown in Figure 3. The line $z = -3000$ AU shows the distance where when jump of density and velocity through the heliopause disappears.
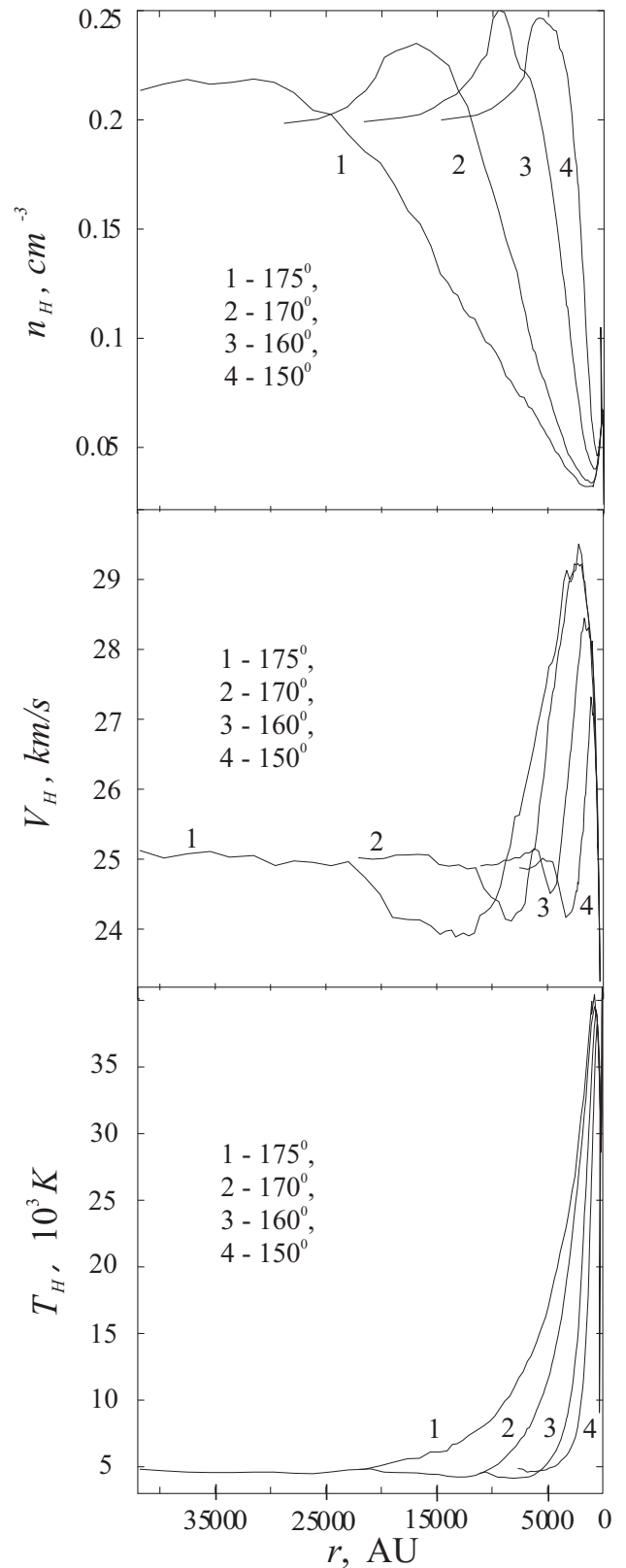

Figure 4: Number density, velocity and temperature of the interstellar H atom along downwind lines of sights $\theta = 150$, 160, 170, 175 degrees.
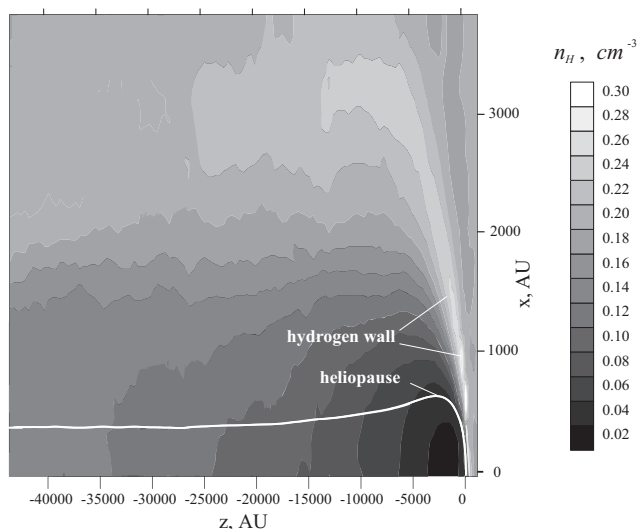
Figure 5: 2D distribution of H atom number density in the heliospheric interface. At heliocentric distances ~ 400000 AU number density of H atoms is closer to the interstellar value. The hydrogen wall, the in crease of H atom number density in front of the heliopause, is also shown. The intensity of the hydrogen wall falls with the increase of the heliocentric distance.

Figures 4 and 5 show the distribution of the interstellar atoms in the tail part of the heliospheric interface. Figure 4 represents the densities, velocities and temperatures of the interstellar hydrogen along the different downwind directions. The angle θ in Figure 4 is the angle between line-of-sight and upwind directions (Figure 1). Parameters of H atoms approach their interstellar values on distances less than 20000 AU for all line-of-sights. The approach is faster for smaller θ. It is interesting to note, that the hydrogen wall, the increase of H atom number density in the region between the heliopause and the bow shock [Baranov et al, 1991; Izmodenov, 2000) is visible even for large $\theta \approx 150 - 170^o$. Two dimensional distribution of H atom number density in the tail region is shown in Figure 5.

It is important that to get numerical solution of the heliotail plasma becomes possible due to the charge exchange process, which makes the solar wind to be supersonic at the outer boundary. This allows fulfilling correct boundary conditions.

In this work we considered influence of the charge exchange process only. In future, influences of different hydrodynamic and plasma instabilities, interstellar and heliospheric magnetic fields on the heliotail structure must to be considered. The processes of reconnection can be also important.

V. SUMMARY

In this paper we consider effects of charge exchange on the structure of the heliotail region. In particular, it was shown that

1. The charge exchange process change the solar wind - interstellar interaction flow qualitatively in the tail region. The termination shock becomes more spherical and Mach disk, reflected shock and tangential discontinuity disappear (Figure 1). The jumps of density and tangential velocity through the heliopause become smaller into the heliotail and disappear at about 3000 AU.

2. Parameters of solar wind plasma and interstellar H atoms approach their interstellar values at large heliocentric distances. This allows to estimate the influence of the solar wind, and, therefore, the solar system size into the downwind direction as about 20000- 40000 AU. Unlike the upwind direction the solar system boundary has diffusive nature in the heliotail.

3. The supersonic character of the solar wind flow in the heliotail allows us to perform correct numerical calculations, which are not possible in the case without H atoms.

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